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HIGH POWER THYRISTORS WITH 5 KV BLOCKING VOLTAGE

K. Lock, H. Patalong and K. Platzoeder

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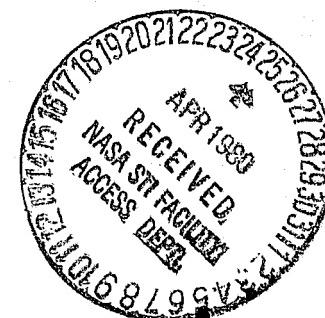


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LIST OF SYMBOLS

ρ	specific resistance
ρ_n	specific resistance of n-base
U_D	off-state voltage
U_R	reverse voltage
U_B	breakdown voltage
v	empirical factor taking avalanche multiplication into account
γ	emitter efficiency
W_n	width of n-base
X	extension of space-charge region
L_p	diffusion length of hole in n-base
U_{RM}	maximum repetitive voltage at given base width
ρ_M	(ρ value appertaining to U_{RM})
θ_{jM}	maximum rated junction temperature
τ_p	hole life-span in n-base
U_T	on-voltage
I_{TAVM}	limiting value of mean forward current
U_{RRM}	repetitive peak reverse voltage, maximum permitted
U_{DRM}	repetitive peak off-state voltage
t_q	circuit commutated turn-off time

HIGH POWER THYRISTORS WITH 5 kV BLOCKING VOLTAGE

K. Loch, H. Patalong and K. Platzoeder
Siemens AG, Munich, West Germany

1. Introduction

1.1 Present Level of Knowledge 1973

In 1973 thyristors having breakdown voltages of up to 10 kV /6* were already known. Because of the unfavorable forward voltage characteristics and the unsatisfactory switching behavior, however, such components assumed only a limited technical importance. The high-power thyristors employed in a variety of applications were designed for peak repetitive off-state voltages of approx. 2.5 kV and transient currents of approx. 13 kA. The breakdown voltage of these components amounted to approx. 3 kV.

Main range of application of such thyristors is in large facilities such as rolling-mill drives and high voltage dc transmission installations. The breaking capacity required for such applications may only be achieved by connecting a large number of individual thyristors. Since the measures necessary for wiring and cooling as well as space required may be considered approximately proportional to the number of thyristors per facility, a further increase in capacity of thyristors leads to a considerable reduction in construction costs and is therefore considered a matter of pressing necessity by plant designers. It must also be taken into account that the operating safety of large facilities generally increases with a decreasing number of components and that for this reason high-power thyristors are desirable.

1.2 Objectives

The aim of the study was outlined in the brief description

* Numbers in the margin indicate pagination in the foreign text.

in Appendix A of our application as follows:

"... to find manufacturing techniques, or to improve known procedures to such a degree that it is possible, by close tolerances and compact dimensioning, to develop a 4.5 kV /7 thyristor, with current-carrying capacity and dynamic characteristics approximating values of known 2.5 kV thyristors."

In the pursuit of this aim we employed the following steps:

2. Problem Segments

2.1 Usage of Neutron-irradiated Silicon

2.1.1 Disadvantages of Conventionally Doped Silicon

An increase in blocking capacity of thyristors can be achieved by increasing the specific resistance ρ_n of the n-base and its width W_n . Low forward voltage losses and good dynamic characteristics, however, require the smallest width of n-base possible. The task of finding a compromise between these two components demands on width is best resolved according to how closely the calculated optimal value of the specific resistance can be achieved.

Maintaining close tolerances when setting the basic doping by means of drawing zones on the silicon rods, however, leads to considerable difficulties when the target value exceeds $100 \Omega\text{cm}$ and the diameter of the rods is more than 40 to 50 mm. Fig. 1 shows four maximum value measurements along the diameter of one silicon disc at beginning and end of rod, respectively. The figure clearly demonstrates the relatively high ρ variations within a disc as well as a drift of the ρ value in the axial direction. In addition the deviation of the average ρ value of the rod from target value must also be considered. In order to contain the deviation within acceptable limits during crystal processing, the

manufacturer of thyristors is forced to permit a relatively wide /8 range of possible ρ values when employing conventionally doped silicon. The consequences of this means of manufacturing are discussed in the next section.

2.1.2 Effects of Variations of Silicon Specific Resistance on the Thyristor Characteristics

According to Herlot [1] the repetitive voltage U_R of a thyristor for a sufficiently large off-stage current may be calculated according to the following equation:

$$\left(\frac{U_R}{U_S}\right)^v = 1 - \frac{\gamma_e}{\cosh(w-x)L_p} \quad (1)$$

In this equation v is a factor taking the avalanche multiplication into account, γ_e the emitter efficiency and L_p the diffusion length of the minority carrier on the n-base. When the dependence of the values U_B and X on specific resistance ρ are taken into account, the relationship $U_R(\rho)$ can be derived from this equation via numerical or graphic methods. These show a flat maximum for U_R at a specific value for ρ . Curve 1 in Fig. 3 presents an example ($\gamma_e = 1$, $v = 6$): these correspond to experimental values at room temperature. For higher temperatures it must be taken into account that the off-stage current may not exceed a certain level to keep off-state power losses down and to ensure the stability of the component. However, if $U_R(\rho)$ is measured with a given off-stage current, the maximum shifts with increasing temperature to ever-decreasing ρ values so far until the increase in charge carrier generation due to temperature is compensated by the decrease of current amplification factor because of the smaller size of space-charge region. Curves 2 and 3 of Fig. 3 show the temperature drift and the more clearly defined maximum repetitive /9 voltage. These were measured using thyristors of conventionally doped material with a relatively low specific resistance, their characteristic, however, is also typical for other ρ regions. To achieve an estimate on the increase of reverse voltage U_R at a given base width W through a narrowing of the permissible tolerance

$\Delta\rho$, it should be assumed that $U_R(\rho)$ may be represented by the breakdown of curve $U_B \sim \rho^{3/4}$ on the low-resistance side of the maximum. The simplification that the curve $U_R(\rho)$ is symmetrical to the maximum leads to the following estimation [2]:

$$\begin{aligned}\Delta U_R &= \pm 0,75 U_{RM} \cdot \Delta \rho / \rho_M && \text{at room temperature} \\ \Delta U_R &= - 0,75 U_{RM} \cdot \Delta \rho / \rho_M && \text{at maximum junction} \\ &&& \text{temperature } \theta_{jm}\end{aligned}\quad (2)$$

where U_{RM} and ρ_m are the values of the maximum at θ_{jm} . Every deviation of $\Delta\rho$ from ρ_m results in a loss of repetitive voltage in the upper temperature region being substantially greater than expected according to equation (1). Equation (2) understandably represents only an approximate estimation as, for example, temperature influence on breakdown curve is disregarded, but the equation does present rather well the degree of macroscopic variations in specific resistance of the source silicon on the blocking capability of thyristors. The following example serves as a further explanation:

The specific resistance ρ of the n-base for a thyristor is determined in a way that a blocking capability of 3,000 V results when base width is minimal and off-stage current is given. Temperature lies within a range of 20 to 125°. If it is assumed that resistance variations within a single disc can be disregarded but that differences in resistance exist from one disc to another of the lot under investigation, the following resistivity voltage band may be observed:

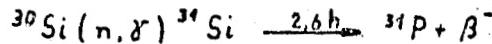
$$\begin{aligned}2.550 \text{ V} &\leq U_R \leq 3.450 \text{ V} && \text{at } 25^\circ\text{C} && \text{for } \Delta \rho \leq 20 \% \\ 2.550 \text{ V} &\leq U_R \leq 3.000 \text{ V} && \text{at } 125^\circ\text{C} \\ 2.910 \text{ V} &\leq U_R \leq 3.090 \text{ V} && \text{at } 25^\circ\text{C} && \text{for } \Delta \rho \leq 4 \% \\ 2.910 \text{ V} &\leq U_R \leq 3.000 \text{ V} && \text{at } 125^\circ\text{C}\end{aligned}$$

In the case of large-surface thyristors the resistance variations within the individual disc cannot be disregarded when employing conventionally doped silicon. When maintaining the values for $\Delta\rho_n/\rho_n$ given in the example, this leads to a lowering of the upper boundary of the tolerance band, since in each case the most unfavorable value within the disc determines the U_R . These statements are in agreement with experience gathered over several years in the manufacture of 800 A, 2.5 kV thyristors.

If silicon with the low ρ tolerance is employed, then the voltage limit in this example may be increased by 300 V without negatively influencing the current carrying capacity and the dynamic characteristics and without affecting the yield. The possible gain in repetitive voltage in conjunction with breaking capacity made experiments with neutron-irradiated silicon seem worthwhile.

2.1.3 Advantages of Neutron-irradiated Silicon

In 1971 Schnöller [3] once again applied a method which had been forgotten for the subsequent doping of highly pure silicon with phosphorus via neutron bombardment. This procedure, already described by Tannenbaum and Mills [4] in 1961, had not achieved any technical importance until then. The generation of doping is achieved through radiation with thermal neutrons in a nuclear reactor. In this process the naturally occurring silicon isotope ^{30}Si is changed into phosphorus ^{31}P according to the reaction:



The degree of alteration and the accompanying doping intended may be achieved for a given neutron density via radiation time. Since the thermal neutrons penetrate the Si-matrix with an even distribution, very good homogeneity of doping is achieved even in the case of rods with a large diameter if only the basic doping of the source silicon lies sufficiently below the target value of final doping before the neutron irradiation. Directly after

radiation the crystalline structure is still so greatly disturbed that the irradiated crystal seems to exhibit high-impedance. By means of a tempering process using temperatures over 1,000 K, however, this damage can be repaired. Further questions concerning this repair process will be dealt with in a separate development project (NT 614). Fig. 2 shows four peak measurements taken on a neutron-irradiated silicon disc of 50 mm diameter. The variations measured after the repair process around the target value of $150 \Omega\text{cm}$ are smaller than $\pm 2\%$. The comparison with Fig. 1 shows the superiority of neutron-irradiation as a doping procedure for phosphorus in comparison to conventional doping procedures during crystal manufacture. A sufficient criterium for the suitability of neutron-irradiated silicon in component manufacturing, however, is supplied solely by component performance. Therefore the breakdown behavior of fully-diffused p_n-diodes of neutron-irradiated silicon was first examined. The width of the weakly doped zone (s zone) was chosen greater than the maximum possible space-charge region width. In Fig. 5 the breakdown voltages measured /12 on these diodes are represented as a function of ρ value of the S_n-base. In the case of diffusion processes the specific resistance was measured with the aid of a four peak test assembly on the discs beforehand and a control measurement was taken again on the finished diodes after lapping off the p-base layer. The alterations resulting in the manufacturing process remained within the measurement accuracy. The relation $U_B(\rho)$ represented in Fig. 5 concurs with measurements on conventional silicon, when for ρ the minimum value of specific resistance within the disc is applied. The deviation of measured values from the theoretical curve according to Sze and Gibbons [5] may be attributed to the influence of non-abrupt pn-transitions. The dependence of breakdown voltage on the temperature is shown in Fig. 6. Fig. 4 shows the reverse characteristic of a 50 mm diameter diode at room temperature in logarithmic representation. The very small off-stage currents for an element with an area of 1.850 mm^2 prove that the radiation damages have been substantially repaired. A corresponding test series on thyristors obtained comparable

results. These positive pretest results were reason enough to develop thyristors with breakdown voltages greater than 3 kV exclusively with neutron-irradiated silicon. More detailed information on this follows in Sections 3 and 4.

2.2 Improvement of Emitter Diffusion Procedure

The characteristics of a thyristor, especially the dynamic characteristics and the losses incurred in current loads, are substantially influenced by the n-emitter. Thus the depth of penetration of the emitter in conjunction with the doping profile of the p-base and the emitter shunts influence the trigger behavior and the local on-state power losses. Accompanying this the gettering characteristic of the highly doped phosphorus regions has a decisive influence on the distribution of the recombination centers and as a result on the recovery time and the turn-off behavior. /13 While there is generally no problem involved in reproducing the lateral emitter geometry by means of known photo etching techniques, maintaining constant reproducible doping profiles in the case of discs with large areas becomes more and more difficult. Aim of the study in this problem segment was to improve the reproducibility and homogeneity of the n-emitter diffusion while maintaining the secondary condition of sufficient efficiency so that even in the case of large disc thickness as is necessary for the manufacture of thyristors with high reverse capabilities, narrow tolerance bands may be maintained in the electrical data.

2.2.1 Gas Doping

The standard procedure is the usual carrier gas diffusion with POCl_3 source. The silicon discs are arranged adjacent and subsequent to each other in ganged quartz [Quarzhorden]; disc surfaces are parallel to the direction of gas flow. For 50 mm discs, however, this arrangement has distinct drawbacks:

1. When lot size is sufficiently efficient the uniformity of distribution is unsatisfactory. Doping decreases in the lower portion of the disc.

2. If the lots applied are not very large, the doping decreases along the flow direction.
3. Spatial filling is poor in the diffusion tube.
4. When ganged quartz is partially devitrified, dislocation may easily occur at points of contact with silicon disc.

In order to make improvements concerning points 1, 3 and 4 /14 trials were conducted with ganged silicon in which the discs were positioned transverse to flow. Fig. 13 shows such a ganged silicon provided with silicon discs. The gang [Horde] represents only a minor obstruction of gas flow. If tube axis and disc center point are approximately in conjunction with one another, a good homogeneity of doping within a disc results. Compare Figs. 7 and 8. The change-over from quartz to ganged silicon also provided the desired effect: fewer displacements and slip bands. As expected, however, the decrease of doping material from one disc to the next in flow direction was not improved. As next trial step the carrier gas enriched with doping material was forced between the discs through jets in the diffusion tube. This measure did indeed supply the desired improvements, but disturbed the rather complicated structure and the low service life of the quartz parts used.

Finally a trial let to success in which the application of doping was pulsed over magnetic valves in intervals of one minute. Uniformity of doping was rather good when magnitude of the lot was economical. The variations in surface conductivity, for example, generally remain below $\pm 5\%$ in a lot of 50 silicon discs of 50 mm diameter. A sensitive test of uniformity of gettering effect of n-emitter was carried out by measuring the minority carrier life in n-base after a gold diffusion. These measurements with a relatively high spatial separation were conducted by Mr. Schwab on thyristor discs at the Institute for Solid-State Technology of the Fraunhofer Association in Munich. Fig. 9 shows a typical topogram of minority carrier life-spans in the n-base in a quarter of a 50 mm diameter thyristor. The light

regions (high τ_p values) designate the n-emitter. The dark regions (low τ_p values) correspond to p-areas on the surface (trigger structure and boundary short circuits). In relation to the difference between /15 the values below p and n-areas, the variations in emitter region may be disregarded. Therefore no attempt was made at the present time to improve the gas diffusion still further.

2.2.2 Doping Varnish

Simultaneous to the trials for gas diffusion improvement the application of doping varnish was tested for its suitability in the manufacture of power thyristors. Of two varnish types of differing viscosity manufactured in the semiconductor plant of Siemens AG, Balanstrasse, Munich, the thinner one was suitable for application with the aid of a varnish sprayer. The homogeneity of coverage achieved was sufficient, but the reproducibility of target values was problematic. In addition, the attainable diffusion lengths for highly blocking thyristors were too low by the factor 3 to 10. At this point the trials were discontinued.

2.2.3 Ion Implantation

As a further method for n-emitter generation, trials were conducted with ion implantation and vapor diffusion. Since the variation of implanted dose is generally given as less than 2%, this procedure seemed very interesting in reference to reproducibility. The question of efficiency did not immediately receive a negative answer with respect to the expected application in high-current machines. Several implantations were carried out in the Institute for Applied Solid-State Physics of the Fraunhofer Association in Freiburg (Dr. Fritzsche, Dr. Axmann) and in the research laboratory of Siemens AG in Munich (Dr. Krimmel, Mr. Runge). The implanted dose varied between 10^{15} cm^{-2} and 10^{17} cm^{-2} , the ion energy between /16 40 KeV and 300 KeV. The results may be summarized as follows:

1. Surface Conductivity

The surface conductivity is very low immediately after

implantation and increases with each tempering until it reaches a final value after the actual diffusion at 1510K (9 h). Temperings at low temperatures, before diffusion takes place, are apparently not necessary for achieving a uniform surface conductivity. The homogeneity of coverage is good, as expected. In the framework of measuring accuracy of the four probe measurements no variations were found.

2. Carrier Life-span

In the case of the few discs, implanted with 100 KeV in the research laboratory, the following connection between the implanted dose and diffusion length L_p was demonstrated:

Dose /cm ²	$1 \cdot 10^{15}$	$2 \cdot 10^{15}$	$8 \cdot 10^{15}$
$L_p/\mu\text{m}$	≤ 10	20-24	115

An increase in L_p related to dose was also demonstrated in discs implanted with 300 KeV in Freiburg:

Dose /cm ²	$2 \cdot 10^{16}$	$> 4 \cdot 10^{16}$	$> 6 \cdot 10^{16}$ ($\approx 1,2 - 17$)
$L_p/\mu\text{m}$	21-32	15-45	155

If the results may not be attributed to coincidences because of the low number of discs, it could be concluded: the greater the dose and the smaller the ion energy, the greater the diffusion length and life-span, respectively. This relationship /17 would not be unexplainable, but it still must be confirmed by further experiments.

The highest diffusion lengths or carrier life-spans attained in the case of implanted discs coincided with the lower limits of the usual values of the gas-doped discs.

3. Oxide Masking

Oxide layers generated in humid oxygen at 1150° C (3.5^{h}) also have a masking effect on the ion implantation, which could be checked by the conduction characteristic of masked surfaces. The masking was, however, not completely satisfactory in our trials. Thyristors with n-emitters manufactured with the aid

of ion implantation demonstrated a much poorer du/dt behavior than comparable thyristors from carrier gas diffusion.

Grindings proved that the emitter shunts were indeed not satisfactorily masked. The cause may possibly lie in the large increase in the boundary concentration of implanted discs (Fig. 10) which occurred independent of dose.

2.3 Improvement of Boundary Geometry

In the case of thyristors with repetitive voltages up to approx. 0.5 kV, generally a double angle structure is employed as boundary geometry, whereby the pn-transition blocking in reverse direction is limited by the steeper direction by the flat angle ($2-5^\circ$). See Fig. 11. In principle a double-angled structure corresponding to Fig. 11 may also be used for higher breakdown voltages, however, it becomes more and more difficult to achieve approximately symmetrical blocking behavior in both directions as voltage increases. Calculations of the potential relationships for such structures [6] demonstrate that the maximum field intensity does not occur at the penetration line of pn-transition through the surface, but rather further inside, in the region of higher p-doping, just underneath the silicon surface. Only in this region is the flat angle actually decisive. This led to our developing a structure similar to a mesa structure (Fig. 12), differing essentially from the step grinding published by Köhl [7] in one point: in the structure chosen by us the flat angle begins approximately $20 \mu\text{m}$ above the pn-transition. Thereby higher field intensities are achieved in the region surrounding the penetration line of the pn-transition, while the maximum field intensity limiting repetitive voltage is still retained further within the structure. According to the generally valid relation:

$$U = \int E(x) dx$$

the attainable voltage is higher in this case.

Via light scanning of blocking transition with voltage load, Krausse (plant for semiconductors of Siemens of AG in Munich) was able to prove experimentally the position of field intensity maxima on components.

Even in the voltage range of 5 to 6 kV we succeeded in achieving symmetry factors of 0.9 for U_D/U_R . In this case U_D is the breakdown voltage in positive and U_R the breakdown voltage /19 in negative direction. With a normal double-angled structure, on the other hand, we were only able to achieve values of approx. 0.8.

The special advantages of the improved double-angled structure as compared to other boundary structures for high voltage, as for example, the previously published variant of the "sheave form," lie in our opinion in two points:

1. The field intensities occurring on the silicon surface are reduced to such a degree that the components already achieve almost complete blocking capacity without protective varnish.
2. The negative blocking direction (U_R) is geometrically so favored that high avalanche loads are possible.

Both points are especially important for the application in high voltage dc transmission installations. We therefore applied the improved double-angle structure to all further investigations.

3. Thyristors with Breakdown Voltages of 3.5 - 5.5 kV

The techniques described in Section 2 provide the basis for further work on high-blocking thyristors. We have parallelly developed two different types on the basis of a unified system diameter of 50 mm. These cover the breakdown voltage region of 3.5 - 5.5 kV with two target values 1 kV apart from each other (4 kV and 5 kV).

3.1 Manufacturing Procedure

Neutron-irradiated silicon in the resistance range between 130 Ω cm to 200 Ω cm was employed as source silicon. In the precision dimensioning of a given breakdown voltage a narrowing of resistance tolerances in the range mentioned to about $\pm 7\%$ seems apt and feasible at the present level of knowledge. The non-irradiated source silicon originates from our production. Material from the Wacker firm was also employed in part. The radiation was mainly carried out in the research reactor at Karlsruhe. The irradiated silicon was processed according to standard methods, beginning with sawing and lapping the crystals. The p-regions are generated via successive diffusions of aluminum and gallium, resulting in the pn-transitions at a depth of approx. 90 μ m. After oxidation in humid oxygen followed by window etching, the emitter diffusion is carried out. Thereby the carrier life-spans within discs increase by means of gettering processes so greatly, that an intended reduction to desired value becomes possible. The reduction is achieved via a gold diffusion. For contacting of p-emitter and for increasing the mechanical stability, the Si wafer is alloyed into a Mo carrier plate by means of an Al intermediate layer. The metallization of n^+ -emitter and the centrally located trigger contact is evaporated using mechanical masks. A photographic etching procedure is available for the generation of fine structures.

The boundary contour is generated by means of sloped lapping. Damage is then removed by a subsequent etching polish. The pn-transitions projecting at the boundary are covered by an elastic silicon rubber. The capsuling of the thyristor wafer is carried out via a flat-pack housing with ceramic insulation and pressure contact on both sides. Fig. 14 shows a thyristor wafer of 50 mm diameter on the left, the corresponding element capsuled on the right. The insulation sections of the 26 mm high capsule are large enough for voltages up to 4.5 kV. The pressure necessary for the element is generated when it is clamped in the heat sink.

3.2 Static Electrical Parameters

Figure 15 shows typical reverse characteristics of a 50 mm /21 diameter thyristor made from neutron-irradiated silicon intended for breakdown voltages of approx. 4 kV. Because of homogeneity of resistance over the disc very sharp avalanche characteristics result. Thyristors constructed in this way are already being produced in series. Fig. 16 shows the total frequency distribution of repetitive voltages attained for a measuring current of 100 mA at the beginning of production.

Resistance tolerance of $\pm 5\%$ of Si material employed is superimposed by an alteration of target value of 10% in a portion of the silicon rods. The effect is recognizable in the knee of the room temperature graph. The scattering of 20° C reverse voltages is only somewhat greater than as is expected based on the above-mentioned estimation of a total of $\pm 10\%$ for a variation

As explained in Section 2.1.2, at 120° C a reduction of 50% of the U_R value is observed, compared to the value at 20° C. Differences in recombination center density and thus in reverse current level lead in combination with the band of possible ρ values to a flattening of the 120° C curve. The relationship of reverse voltages for both polarities U_D/U_R is better than 0.91 for 50% of the elements. Increasing wafer temperature further improves symmetry.

The gold dose was set for achieving sufficiently low circuit commutated turn-off times and storage charges, as are required for high voltage dc transmission installations, so that the on-voltages U_T represented in Figs. 17 and 18 result. In combination with a heat resistor of 0.22 K/W a permissible limiting value of mean forward current I_{TAVM} of 800 A is achieved at a housing temperature of 74° C. The current load capacity of thyristor wafer is characterized better by the surge forward current than by the limiting

value of mean forward current dependent on cooling conditions. /22
It amounts to 16,500 A at 20° C, corresponding to a maximum load integral $\int i^2 dt$ (10 msec.) of 1,3500,000 A² sec.

Thyristors with breakdown voltages of approx. 5 kV were manufactured with the same production techniques as for thyristors with breakdown voltages of approx. 4 kV. In order to achieve this the specific resistance of source material and the n-base width were increased to values of 200 Ωcm and 800 μm, respectively.

Figures 12 and 20 show the reverse and on-voltage characteristics of these thyristors. Since development work in the framework of this project was intentionally limited to the 50 mm format, the current-carrying capacity of the component is smaller than that of the thyristor with a typical breakdown voltage of 4 kV developed parallelly to it. In the technical applications of thyristors the physical concept of breakdown voltage only plays a role in avalanche components. More important is the concept of the highest permissible periodic repetitive peak reverse voltage and repetitive peak off-state voltage. (U_{RRM} and U_{DRM} , respectively). These voltage values generally lie 10% under the breakdown voltages achieved at room temperature. The voltage reserve of 10% up to the actual breakdown is necessary to balance out measuring inaccuracies and the decrease in breakdown voltage at temperatures lower than room temperature. Therefore a U_{RRM} and U_{DRM} of maximum 3.5 kV is given for the thyristor with 4 kV breakdown voltage and for the thyristor with 5 kV breakdown voltage a maximum of 4.5 kV.

Figure 21 shows a comparison of three distinct thyristor types in 50 mm format differing in their characteristics in respect to U_{RRM} . A flat maximum at approx. 3.5 kV results in breaking capacity ($U_{RRM} \times I_{TAVM}$). This applies for circuit comutated turn-off time of approximately 400 μsec according to German industrial standards (DIN), sufficient for normal line applications.

3.3 Dynamic Characteristics

The most important dynamic characteristics of thyristors for line applications are the permissible rate of rise of off-state voltage di/dt and the circuit commutated turn-off time t_q . /23 In respect to du/dt loads, modern thyristors are very robust in complete diffusion techniques. Practically all of our 3.5 kV and 4.5 kV thyristors withstand voltage increases to full voltage use in 1 μ sec. These values lie far above the normally indicated 1,000 V/ μ sec according to the German industrial standards. Special measures for du/dt improvement were therefore not necessary within the framework of the research project.

The di/dt loads are more critical in the case of highly blocking thyristors than du/dt loads. Expansion velocity of triggering decreases with increasing disc thickness. In order not to arrive at current densities not permissible during turn-on time, we have applied the principle of the integrated auxiliary thyristor ("internal gate trigger current amplification"). In Fig. 14 the annular auxiliary cathode is easily recognizable. The auxiliary thyristor is triggered with the aid of the trigger impulse. This load current, which may be a multiple of trigger current, switches, with a delay of a fraction of a μ sec, the main thyristor into a substantially greater triggering line than would be possible with the actual trigger impulse. In the case of frequency thyristors this current amplification principle, similar to the Darlington transistor, has already been applied successfully for years. It was determined that also in the case of high-blocking thyristors it is suitable for improvement of di/dt behavior. There are practically no failures in the routine tests of 3.5 kV (U_{RRM}) thyristors with a transition current of 150 A from an RC wiring with subsequent di/dt of 60 A/ μ sec to 2,200 A according to conditions set by the German industrial standards. Several samples with branching auxiliary cathodes were also produced to arrive at still more rapid triggering of the entire thyristor surface. The results were positive, but the application of this complicated structure is probably not worthwhile in system

diameters of less than 50 mm, at least at the present level of /24 instrument technology.

The third important dynamic characteristic studied was the behavior of circuit commutated turn-off time of high-blocking thyristors. Improvement measures were the association of neutron-irradiated silicon (decrease of n-base width) and the exact control of n-emitter diffusion to be able to achieve optimal effect of emitter shunts. Without employing negative control voltage, i.e., in normal operation we achieved typical turn-off times in the case of 3.5 kV (U_{RRM}) thyristors according to German industrial standards of approx. 280 μ sec up to an upper limit value of 350 μ sec (limit temperature $120^{\circ} C$), corresponding to values required in high voltage dc transmission installations. To achieve limiting values of mean forward current in a range of interest when using the 4.5 kV (U_{RRM}) thyristor the gold dose was set lower and typical turn-off times of 400 μ sec with an upper limit value of 500 μ sec achieved. Since the number of samples of 4.5 kV thyristors produced is too small for final conclusions, the values involved are preliminary. These turn-off times are sufficient for the line application, for high voltage dc transmission installations they are too high. In principle there seems to be no difficulty in decreasing turn-off times by intensifying gold doping, but the required current-carrying capacity of approx. 800 A can then only be achieved via a further increase in format.

4. Discussion and Conclusions

In the frame of this research project two important questions for the manufacture of highest-blocking thyristors were answered:

1. Does neutron-irradiated silicon solve the question of material?
2. Can manufacturing techniques be found resulting in usable /25 yield in the production of large-surface thyristors with

permissible periodic repetitive peak reverse voltages
of 3.5 - 4.5 kV?

The following can be said about question 1:

The intended accuracy and the homogeneity of specific resistance of neutron-irradiated silicon is not achieved in the range under examination ($\rho_n > 100 \Omega\text{cm}$) even nearly as well by any other doping procedure known to us. Laboratory experiments, in addition to results of current thyristor production have shown that these advantages of neutron-irradiated silicon are not weighed down by any appreciable drawbacks. In particular sufficiently long carrier life-spans may be set in the components as in conventionally doped silicon.

Question 2 may be answered just as positively:

Manufacturing techniques could be improved to the point where thyristors with permissible periodic repetitive peak reverse or off-state voltages between 3.5 and 4.5 kV and limiting value of mean forward currents of 600-800 A can be manufactured today in the numbers the market demands. Of the two high-blocking thyristors developed in the name of the research project, the variant of higher current capacity is already being employed in rolling mill drives and in the valves being produced for the high voltage dc transmission installation at Nelson River. With corresponding demand there seems to be no problem in increasing the current load capacity of this version to 800 A by increasing size.

Therefore we consider the aims of the research project to be met.

Acknowledgement

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The authors wish to thank the Institutes for Solid State Technology and for Applied Solid-State Physics of the Fraunhofer Association for the indispensable aid in the questions of ion implantation and life-span measurement. We further wish to thank Mr. Sonntag of AEF with whom we conducted an enlivening exchange of opinions and results in the course of this research project.

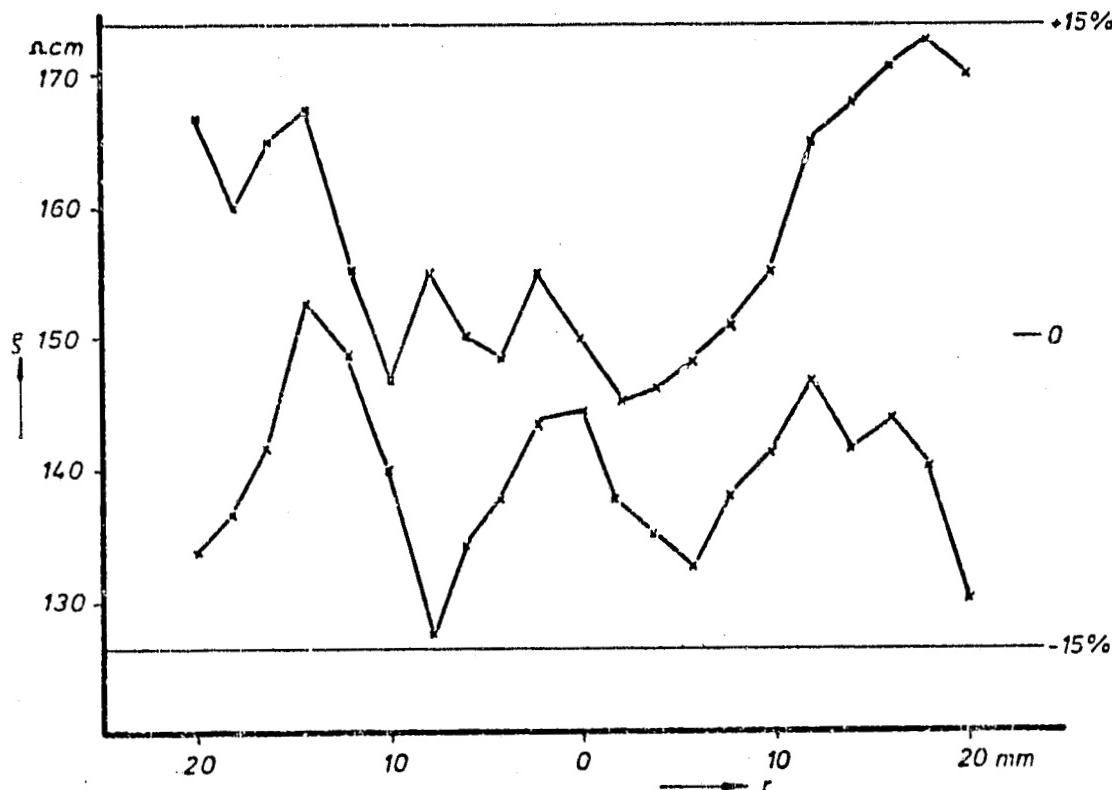


Fig. 1: Radial distribution of specific resistance of a conventionally doped silicon rod, measured on one disc each at beginning and end.

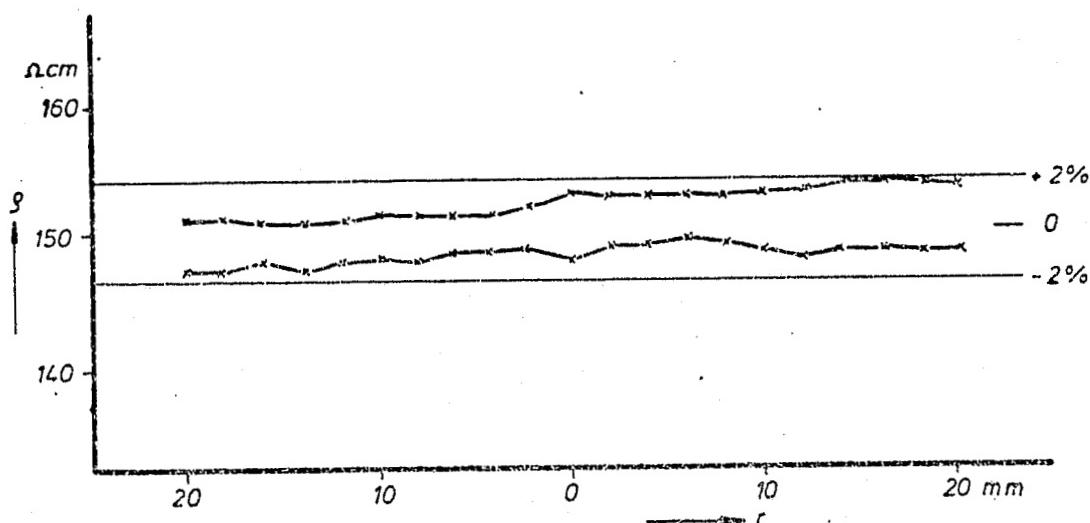


Fig. 2: Radial distribution of specific resistance of a rod doped by means of neutron-irradiation, rod beginning and end.

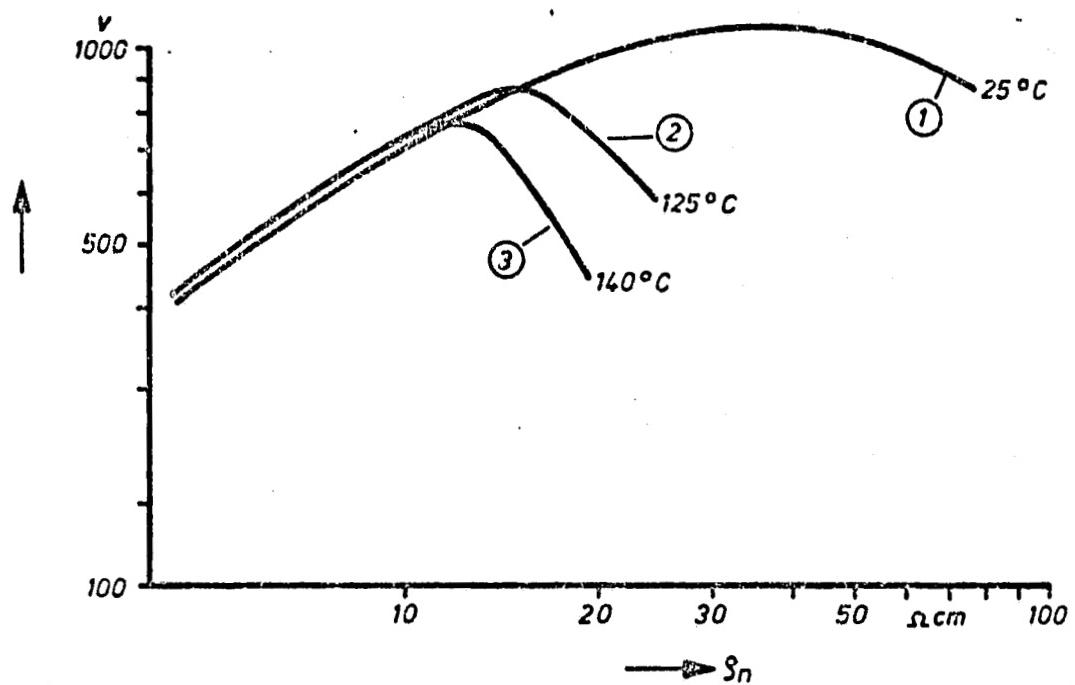


Fig. 3: Repetitive voltage of rapid thyristors with base width of 120 μm and silicon diameter of 25 mm, measurement with a 25 mA blocking current.

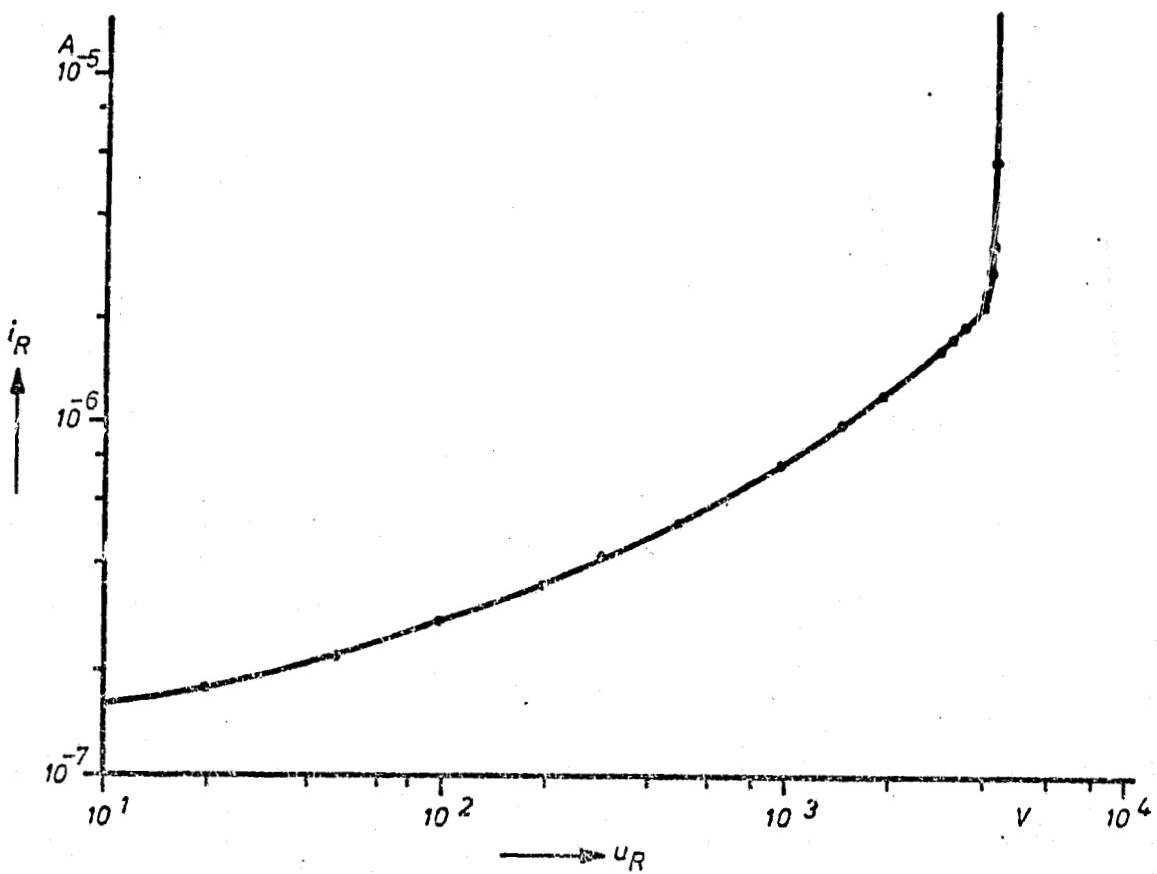


Fig. 4: Blocking characteristic of a 50 mm diameter diode from neutron-irradiated silicon.

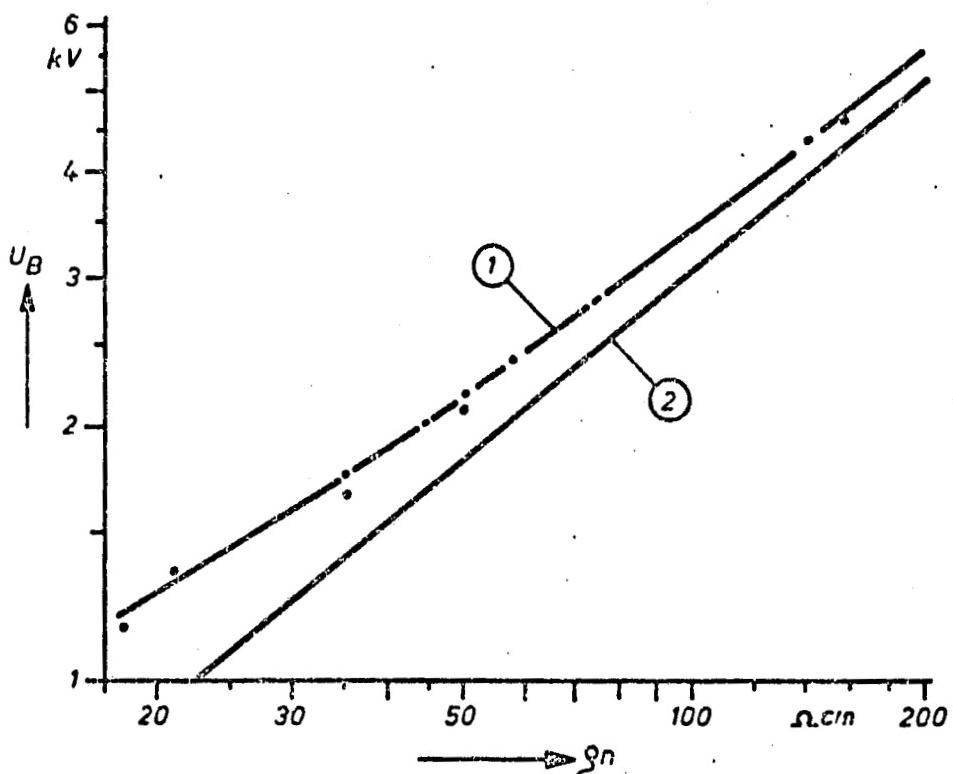


Fig. 5: Breakdown voltage U_B as a function of specific resistance
 1 Own measurement ($\theta = 20^\circ \text{ C}$) 2 Calculated curve for abrupt pn-transitions according to Sze and Gibbons

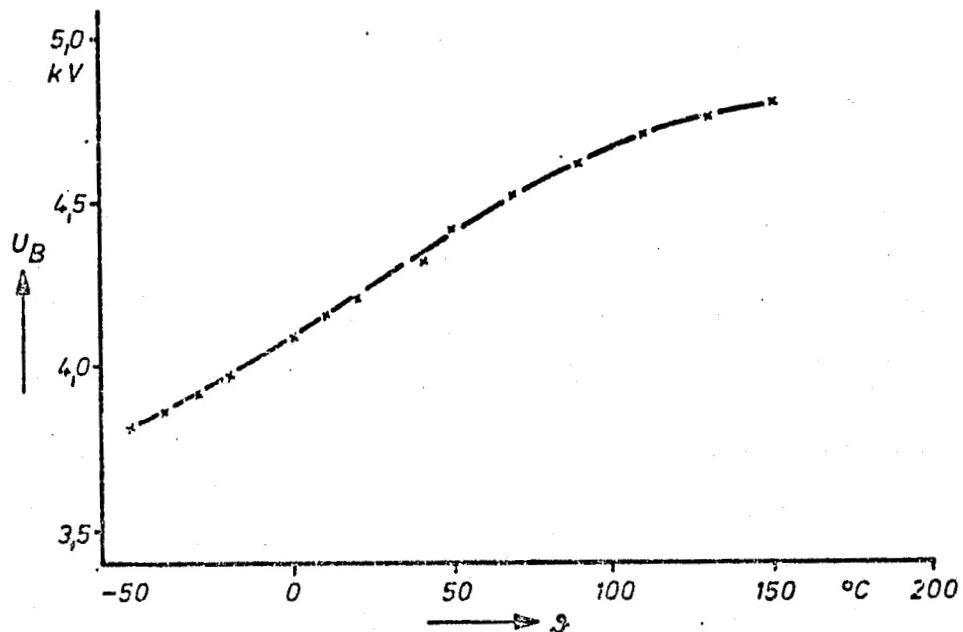


Fig. 6: Dependence on temperature of breakdown voltage.
 Measurement of neutron-irradiated material at $\rho = 138 \Omega \text{cm}$.

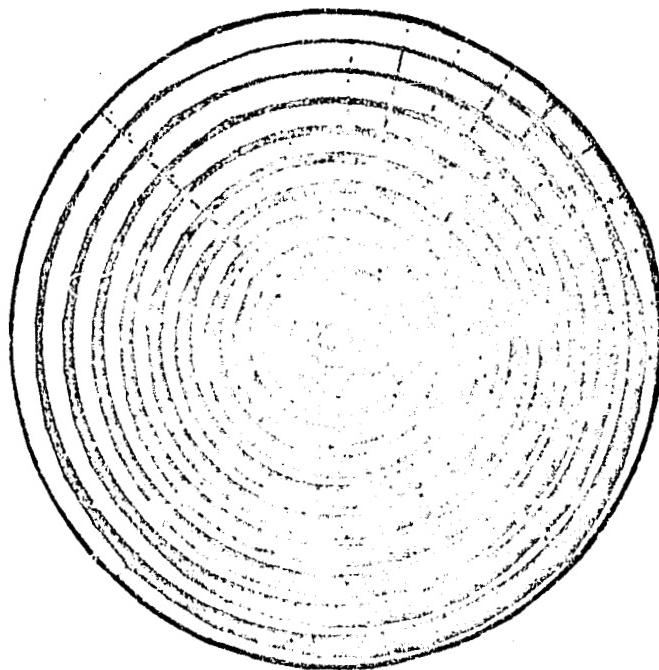
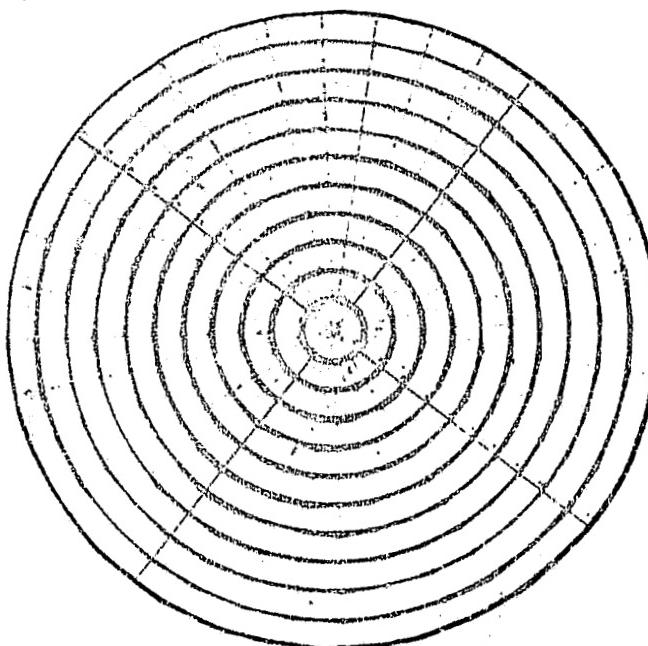


Fig. 7: Distribution of surface resistance after phosphorus diffusion in ganged quartz. Blackened areas represent the local value of $\Delta R = R_s - R_{\min}$, where R_{\min} is the minimum value of disc. Distance between two circles corresponds to $\Delta R = 0.8 R_{\min}$



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Fig. 8: As above, however diffusion in ganged silicon with disc perpendicular to flow direction.

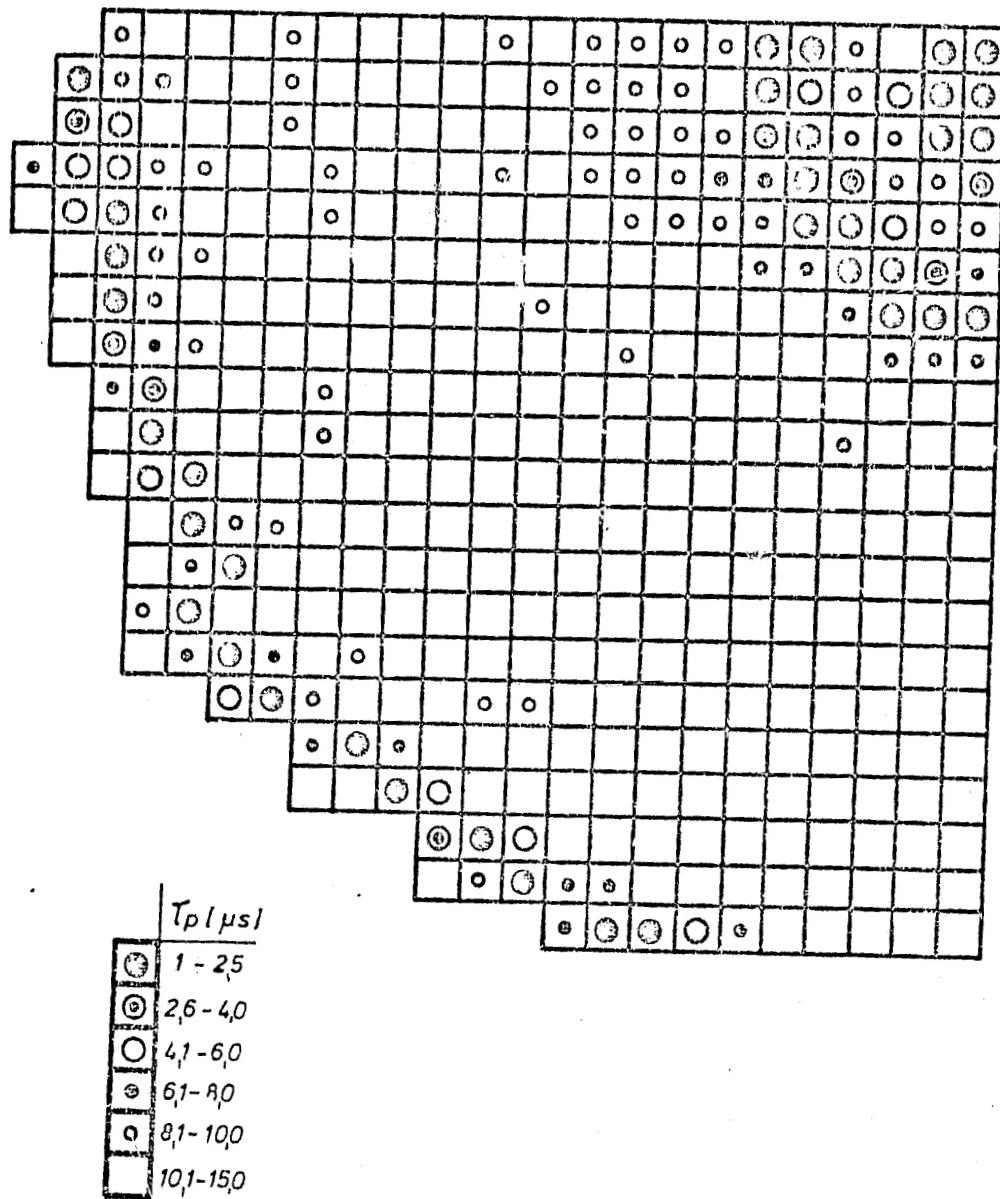


Fig. 9: Minority carrier life-span t_p in n-base of thyristor
 with 50 mm diameter disc.
 Right upper corner: thyristor with trigger contact
 and auxiliary thyristor with trigger amplification.

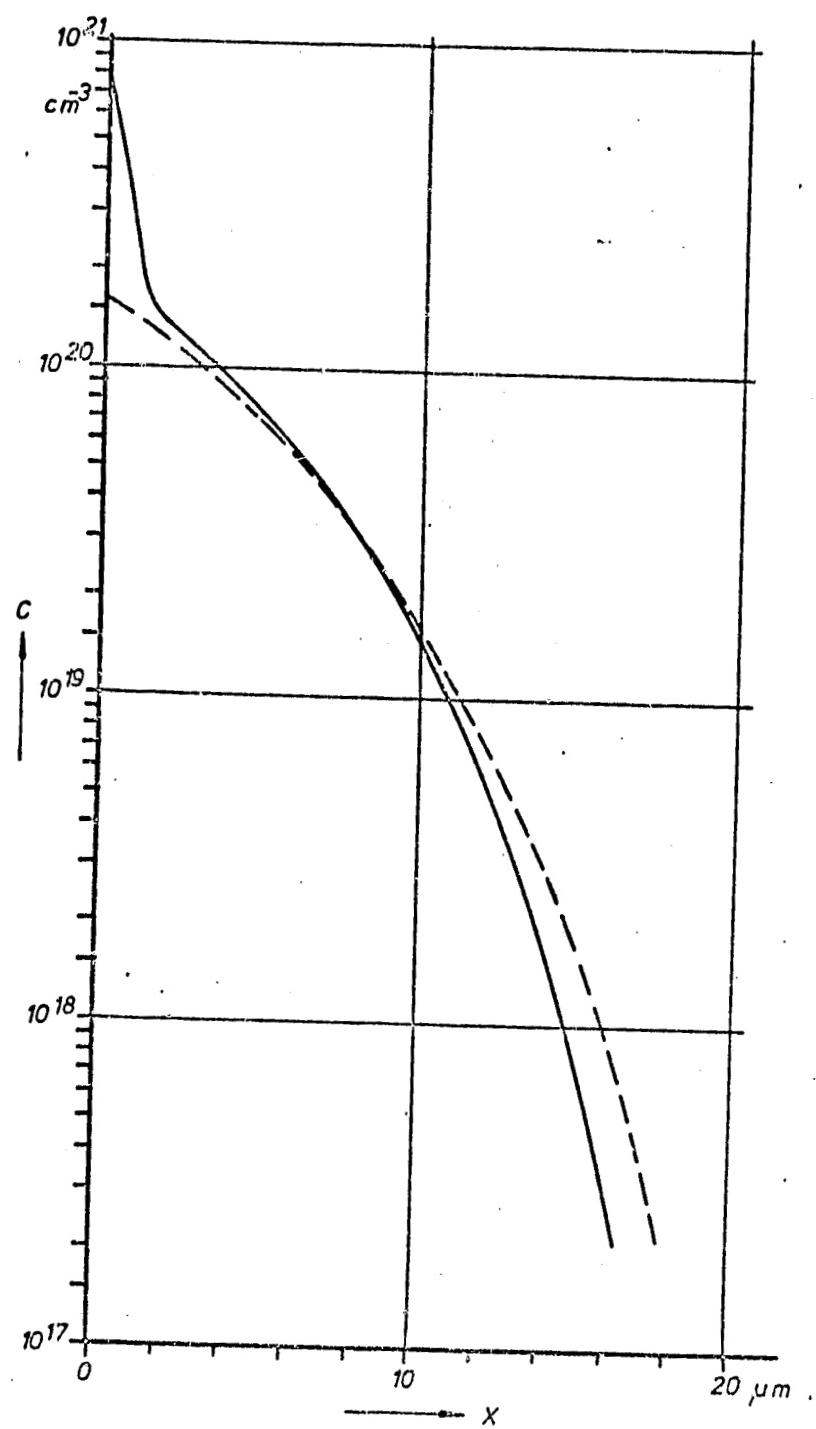


Fig. 10: Profile of phosphorus concentration in an implanted and a carrier gas diffused disc.

— Ion implantation, dose $1.2 \times 10^{17} \text{ cm}^{-2}$. Subsequently diffused.
 - - - Carrier gas diffusion, 1240° C , 9 hours.

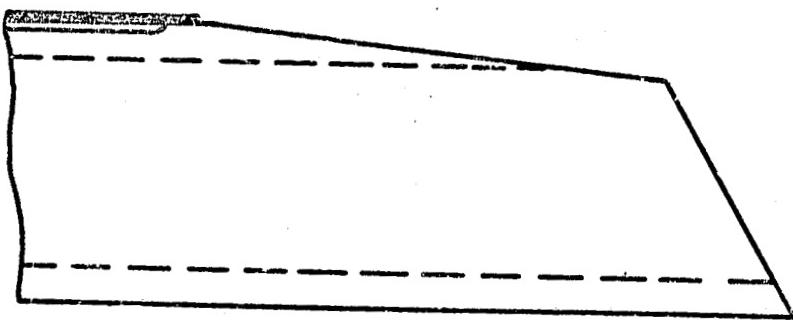


Fig. 11: Conventional double-angled boundary profile.

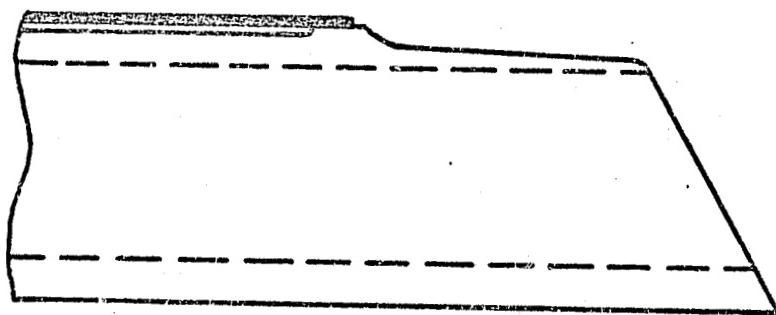


Fig. 12: Newly developed boundary profile.

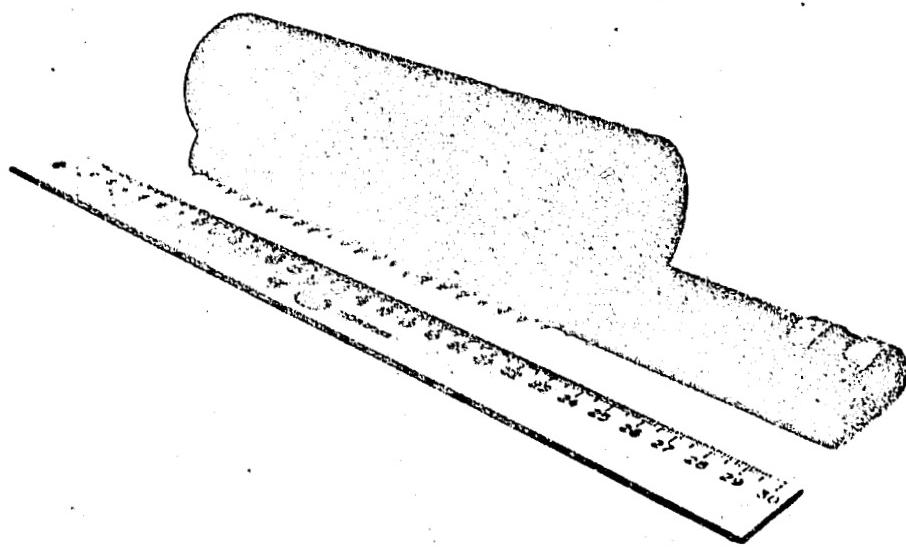


Fig. 13: Silicon for phosphorus diffusion, provided
with 50 mm diameter discs.

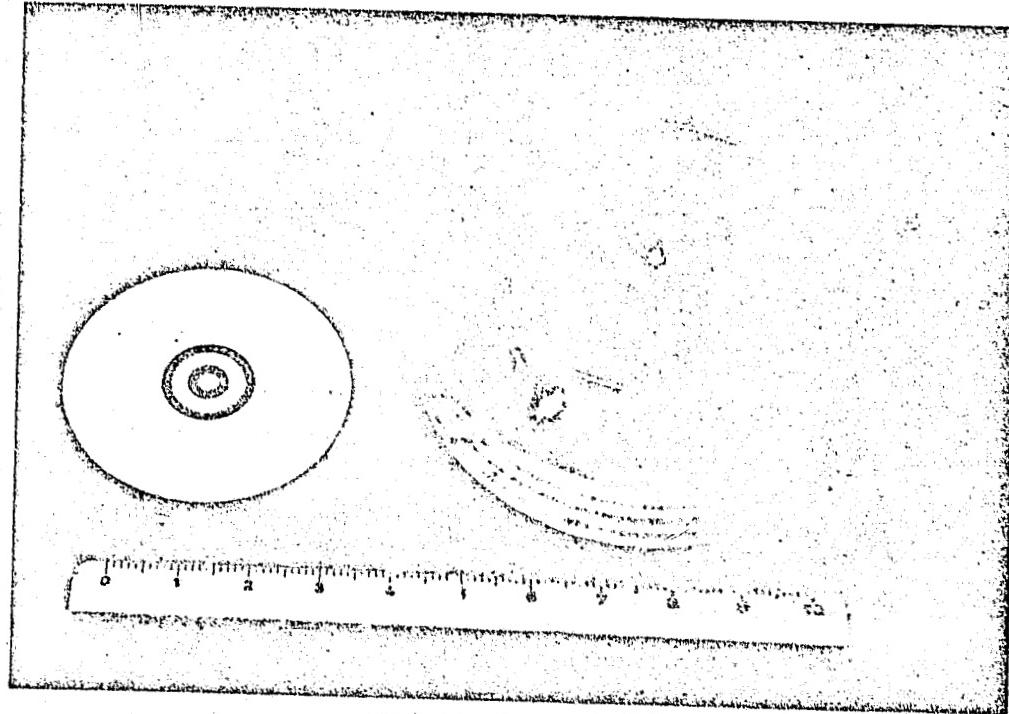


Fig. 14: 3.5 kV thyristor.
Left: thyristor wafer
Right: Flat-pack capsule

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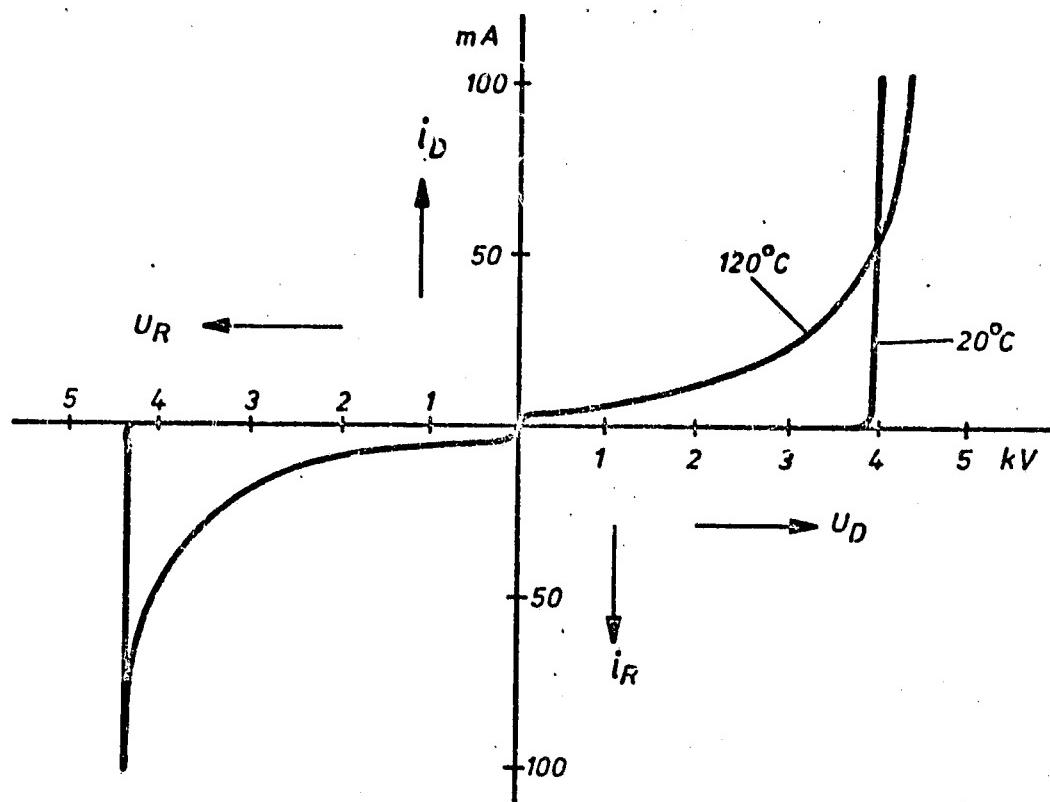


Fig. 15: Typical characteristic curve of 3.5 kV thyristor.

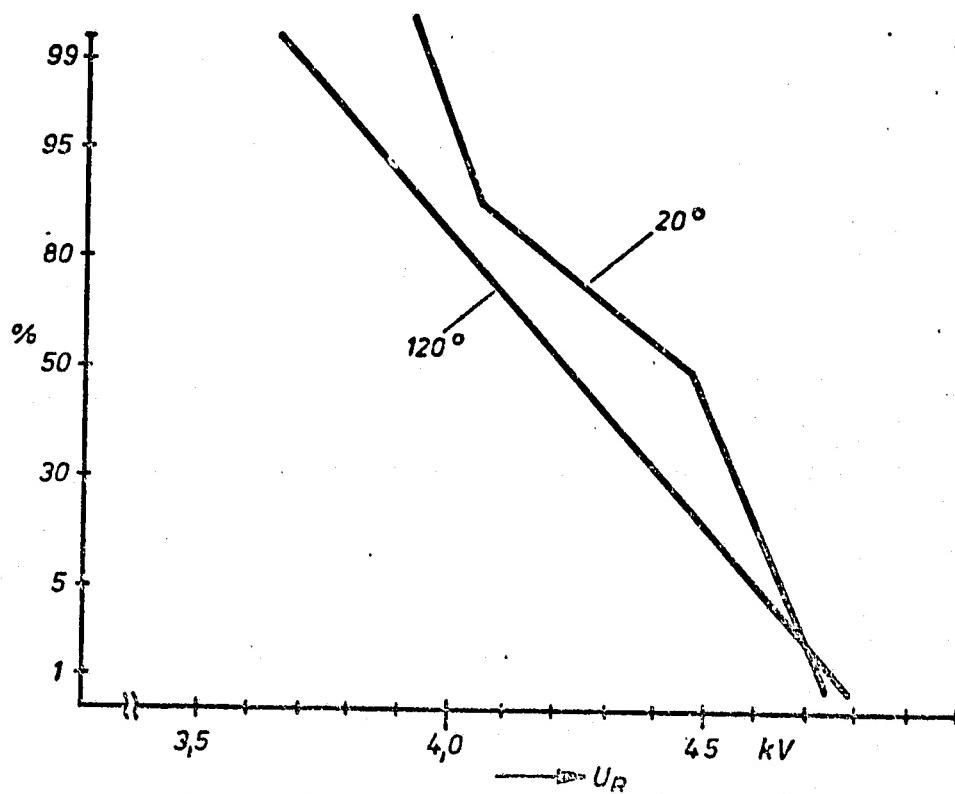


Fig. 16: Repetitive voltage statistics of 900 samples of 3.5 kV thyristors.

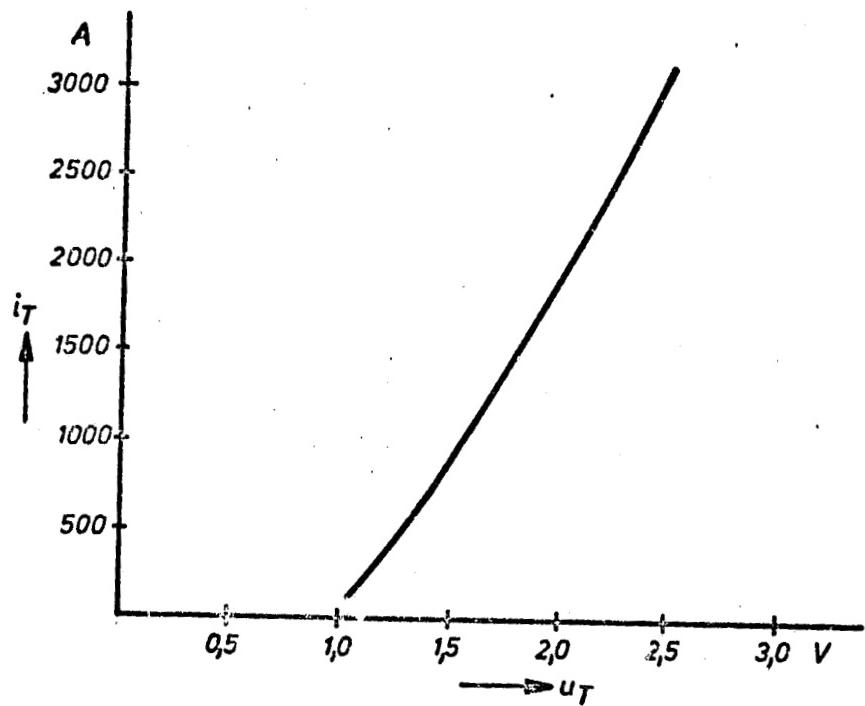


Fig. 17: Typical forward characteristic of 3.5 kV thyristor.

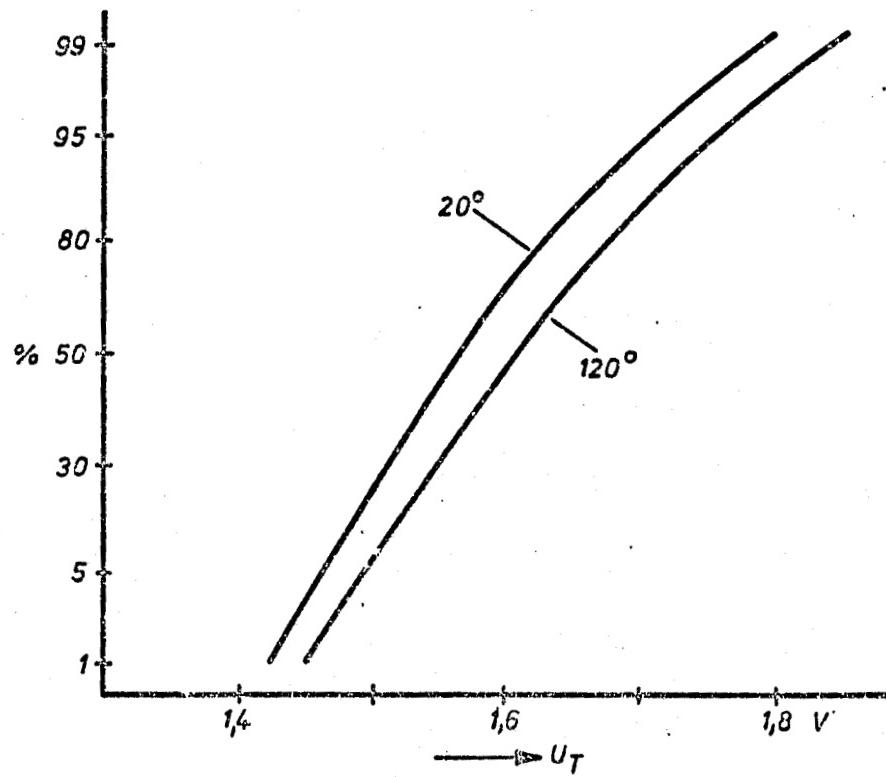


Fig. 18: Statistics of forward voltage loss U_T of 3.5 kV thyristor, measured at $i_T = 1200$ A (900 samples).

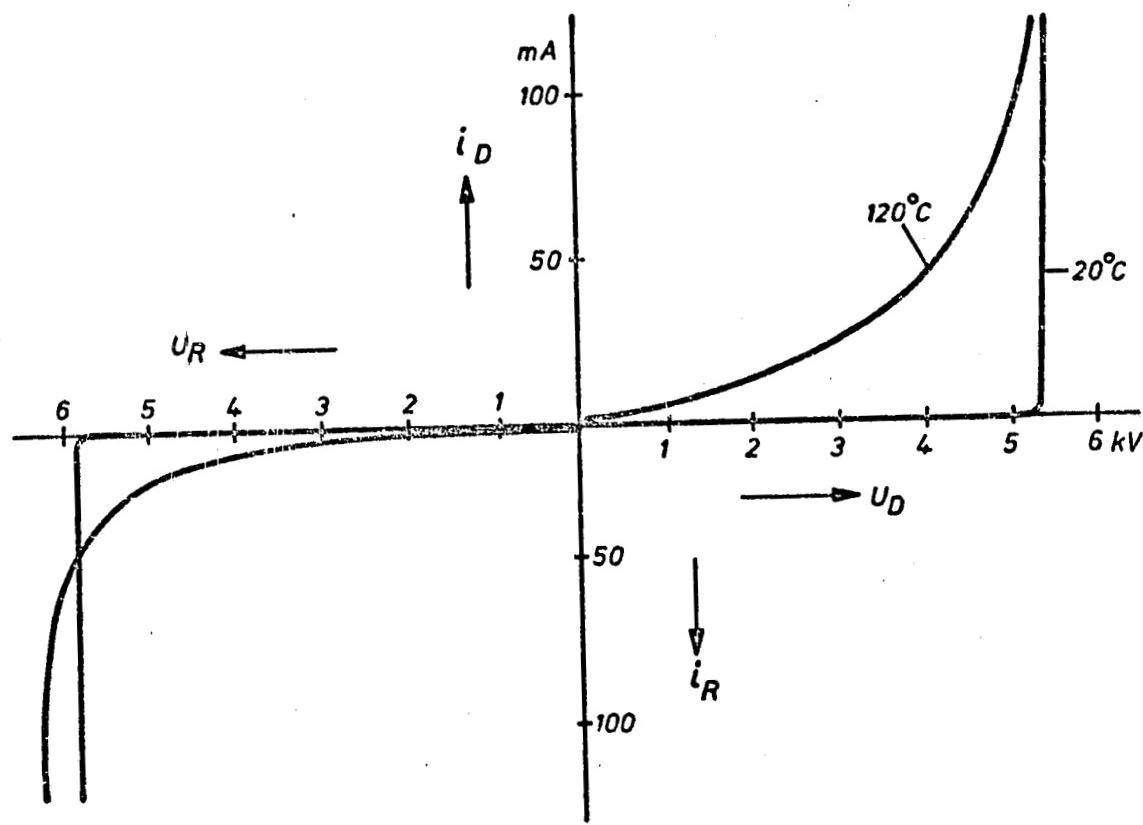


Fig. 19: Typical blocking characteristic of 5 kV thyristor.

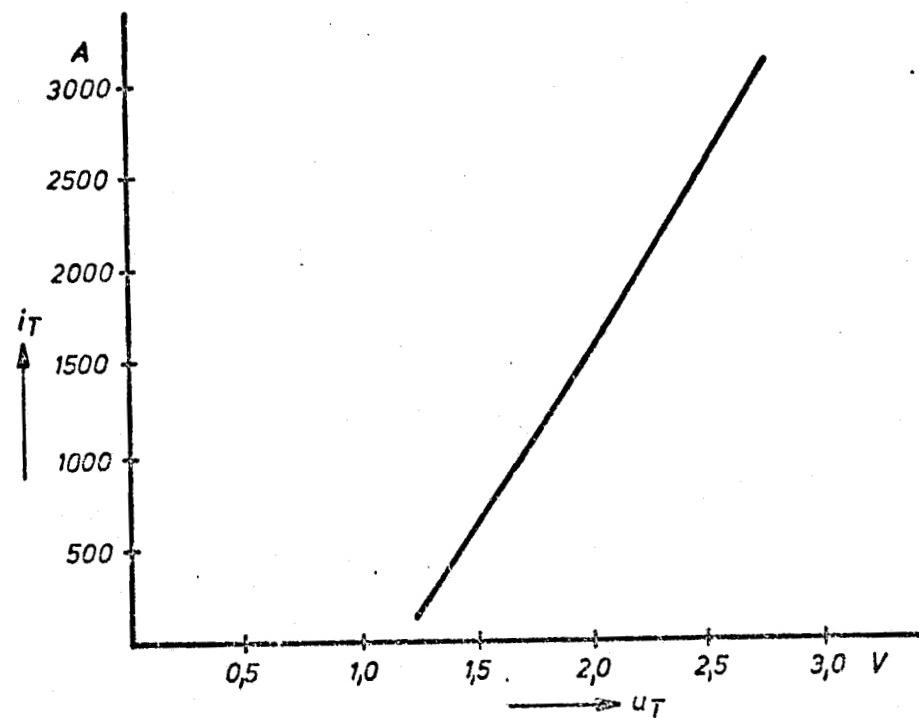


Fig. 20: Typical forward characteristic of 5 kV thyristor.

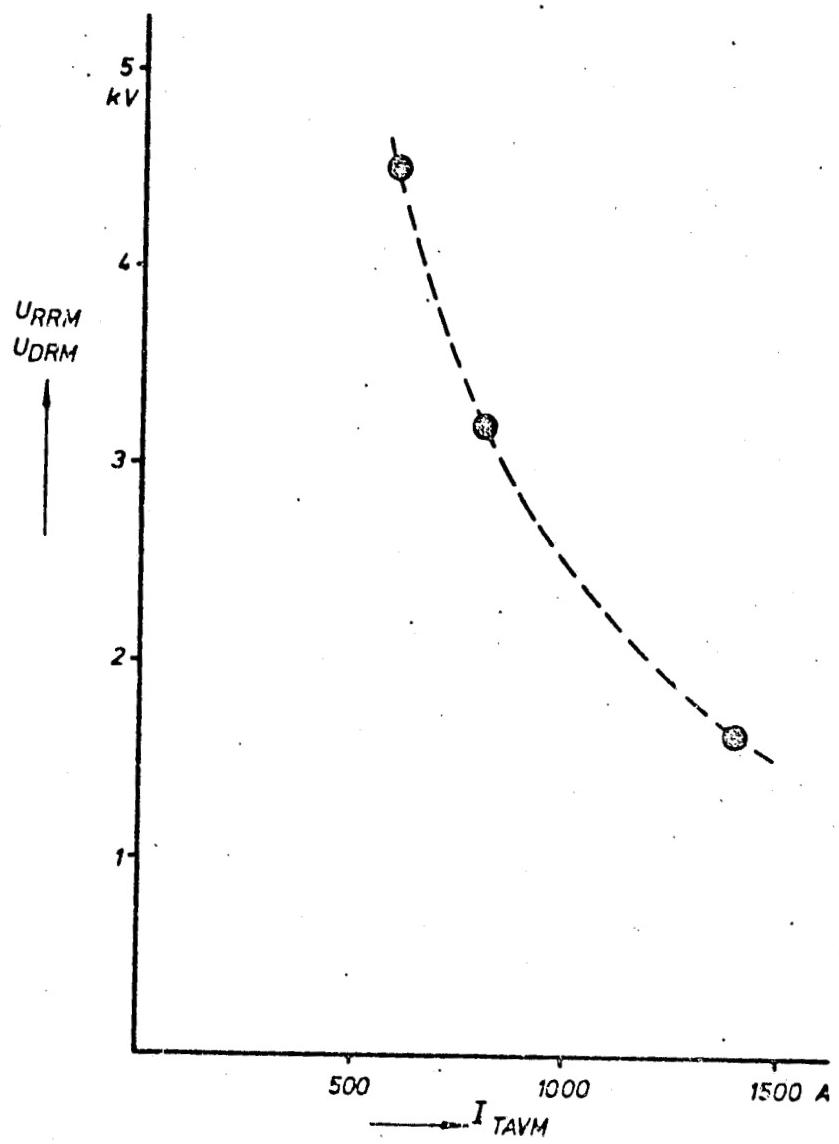


Fig. 21: Max. permissible periodic peak repetitive voltage and limiting value of mean forward current of three 50 mm diameter thyristors of different design.

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